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MODELLING OF HEAT AND MOISTURE LOSS THROUGH NBC ENSEMBLES (U)

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DEFENCE RESEARCH ESTABLISHMENT OTTAWA
TECHNICAL NOTE 91-39

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Abstract

This report summarizes work done to model the heat and moisture transport through various NBC clothing ensembles. The analysis involves simplifying the three dimensional physical problem of clothing on a person to that of a one dimensional problem of flow through parallel layers of clothing and air. Body temperatures are calculated based on prescribed work rates, ambient conditions and clothing properties. Sweat response and respiration rates are estimated based on empirical data to provide appropriate boundary conditions at the skin. Core and skin temperatures are calculated during the analysis and reported as functions of time for four different clothing ensembles. Evaporative heat loss was found to be the dominant heat loss mechanism. Estimates of the rate of sweat evaporation through the clothing ensembles is made. The predicted temperature responses, although not exact, are comparable to results from physiological experiments but somewhat lower. Work tolerance times were predicted to be longer than that found experimentally.

Résumé

Ce rapport résume le travail fait pour modeler le transport de chaleur et d'humidité à travers différents ensembles de vêtements NBC. L'analyse implique la simplification du problème physique à trois dimensions des vêtements sur une personne à celui, à une dimension, de l'aération à travers des couches parallèles de vêtements et d'air. Les températures corporelles sont calculées à partir des échelles de travail prescrites, des conditions ambiantes et des propriétés des vêtements. La sueur et le taux de respiration sont estimés à partir d'une donnée empirique pour fournir les conditions limites appropriées à la peau. Les températures, interne et de la peau, sont calculées durant l'analyse et rapportées en fonction du temps pour quatre ensembles de vêtements différents. Une perte de chaleur par évaporation s'est avérée être le mécanisme de perte de chaleur dominant. Des estimés du taux d'évaporation de la sueur à travers les vêtements sont faits. Les résultats de températures prédits, même si non exacts, sont comparables, bien que moindres, aux résultats d'expériences physiologiques. Les temps de tolérance au travail rencontrés lors de l'expérience étaient plus courts que ceux anticipés.

Executive Summary

Use of the current Canadian Forces (CF) Nuclear, Biological and Chemical (NBC) protective suit in warm environments has shown that the soldier can be subjected to considerable heat stress. New concepts in NBC protective ensembles that are less heat stressful yet provide adequate chemical protection for the soldier are being explored. One key aspect of this work is the prediction of the heat stress incurred while working in these garments.

Physiological experiments are time consuming to perform and contain uncontrollable variables, not the least of which is the human subject. This makes screening of a large number of candidate ensembles tedious and expensive. The variability of the human body can often make interpretation of the results difficult and separation of the various components of heat loss from the total heat loss would require instrumentation not generally available. Numerical analysis is an alternate, complimentary method to the physiological experiments in order to predict the heat and mass transfer.

The physics of heat and moisture transport is a widely studied branch of science and the mechanisms involved are known, at least qualitatively. Numerical modelling is frequently used to solve the governing equations of heat and mass transport. On the basis of theoretical analyses and empirical observations, it is possible to adequately model the flow of heat and moisture for many problems. Analyses of this type can be as complex or as simple as required, however, computer limitations constrain the analysis to relatively simple geometries. They can also provide detailed information on the flow of heat and moisture through the clothing, something that is typically difficult in physiological experiments. What they cannot do, generally speaking, is adequately model the human body for which the physics is less well understood. Although some numerical models of the body exist, they are either limited in scope or rely to a great extent on empirical relationships to determine physiological responses to varying conditions.

In this report, the heat and moisture transport is modeled from a person working in a hot environment while wearing various NBC ensembles. This is done using a simple resistive electrical circuit analogy to the thermal problem. For the most part, capacitive effects are ignored although the heat capacity of the body is used to predict core and skin temperature changes. The analysis allows for: work/rest cycles of specified durations and intensities; specified but constant ambient temperature and relative humidity; specified thermal and water vapour resistance properties of the NBC ensembles.

Some physiological trials have been performed [McLellan 1991] involving the clothing ensembles which were studied numerically. This experimental data allows a useful, if not necessary, evaluation of the validity of the numerical results. The physiological trials where conducted in an environmentally-controlled chamber during which rectal temperature, skin temperature and metabolic rate were measured.

Solar radiation was not considered in this analysis although it can be very important in heat stress studies if not dominant in some cases. Some studies have been made [Breckenridge 1971], however, work remains to be done. Solar radiation was not included in the physiological trials either.

In highly air-permeable clothing, the conductive heat transfer and evaporation rate can be enhanced significantly by convection through the clothing by the wind. Forced ventilation of the clothing was also omitted from the analysis as it requires a good deal of further study before it can be confidently included. Wind was not thought to be a significant factor in the physiological trials as subjects walked on a treadmill or rested in the environmental chamber where air flow speeds are low.

Four different versions of protective clothing ensembles were studied. These ensembles are the current Canadian Forces (CF) Nuclear, Biological, Chemical (NBC) Protective Suit; the NBC suit over combat fatigues; an experimental vapour protective garment developed at Defence Research Establishment Ottawa (DREO) referred to as the Interim suit; the Interim suit worn under combat fatigues. In all of the ensembles, the CF respirator was worn over the face, the CF NBC gloves where worn over the hands and the CF NBC overboots were worn over the CF Combat Boots.

Of the four ensembles studied, the Interim suit worn alone was found to cause the least amount of heat stress. This was primarily due to its greater evaporative heat loss resulting from its lower water vapour diffusion resistance. Indeed, evaporative heat loss is the only mechanism which keeps the body temperatures within safe limits in an environment in which the dry bulb temperature and radiant temperature are both greater than the skin temperature. When the Interim suit was worn under combat fatigues, the incurred heat stress was predicted to be the same as that for the NBC suit worn alone. The NBC suit was found to be the most heat stressful due to its high resistance to water vapour diffusion.

The results indicate that, for a hot environment, an ensemble with a high thermal resistance but with a very low water vapour diffusion resistance would be ideal. This may be increasingly true when solar radiation enters into the problem. Unfortunately, high thermal resistance often implies high water vapour diffusion resistance in passive clothing ensembles. In order to meet both objectives, an active or wind ventilated system is likely required in which the thermal resistance is by-passed by forced ventilation close to the body.

The differences between the model and experimental results were occasionally significant, however, in most cases the results were comparable. There was qualitative agreement in all cases. The differences reinforce the idea that the two evaluation techniques are complimentary, each with its own advantages and disadvantages.

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1.0 Introduction

Use of the current Canadian Forces (CF) Nuclear, Biological and Chemical (NBC) protective suit in warm environments has shown that the soldier can be subjected to considerable heat stress. New concepts in NBC protective ensembles that are less heat stressful yet provide adequate chemical protection for the soldier are being explored. One key aspect of this work is the prediction of the heat stress incurred while working in these garments.

Physiological experiments are time consuming to perform and contain uncontrollable variables, not the least of which is the human subject. This makes screening of a large number of candidate ensembles tedious and expensive. The variability of the human body can often make interpretation of the results difficult and separation of the various components of heat loss from the total heat loss would require instrumentation not generally available. Numerical analysis is an alternate, complimentary method to the physiological experiments in order to predict the heat and mass transfer.

The physics of heat and moisture transport is a widely studied branch of science and the mechanisms involved are known, at least qualitatively. Numerical modelling is frequently used to solve the governing equations of heat and mass transport. On the basis of theoretical analyses and empirical observations, it is possible to adequately model the flow of heat and moisture for many problems. Analyses of this type can be as complex or as simple as required, however, computer limitations constrain the analysis to relatively simple geometries. They can also provide detailed information on the flow of heat and moisture through the clothing, something that is typically difficult in physiological experiments. What they cannot do, generally speaking, is adequately model the human body for which the physics is less well understood. Although some numerical models of the body exist, they are either limited in scope or rely to a great extent on empirical relationships to determine physiological responses to varying conditions.

In this report, the heat and moisture transport is modeled from a person working in a hot environment while wearing various NBC ensembles. This is done using a simple resistive electrical circuit analogy to the thermal problem. For the most part, capacitive effects are ignored although the heat capacity of the body is used to predict core and skin temperature changes. The analysis allows for: work/rest cycles of specified durations and intensities; specified but constant ambient temperature and relative humidity; specified thermal and water vapour resistance properties of the NBC ensembles.

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2.0 Theory

2.1 Assumptions

Since the human body is very complex, it was modeled in a very limited sense, relying on empirical relationships to describe body responses to changing variables. It was assumed that the body could be divided into two regions. The core region was assumed to comprise 90% of the total body mass and all of the metabolic heat was generated here. The skin region comprised the remaining 10% of the total body mass. Heat was transferred between the core and the skin by conduction. The thermal resistance between the core and skin regions was assumed to be 0.025 m^2K/W which is characteristic of vasodilated individuals [Burton 1955]. There was also heat loss from the core associated with respiration for which the expired air was assumed to be at core temperature and fully saturated. Heat could be transferred between the skin and the adjacent clothing ensembles by conduction and radiation. Moisture could simultaneously be transferred from the skin by evaporation and diffusion which results in evaporative heat loss from the skin.

It was assumed that the total surface area of the body was 1.8 m^2 and the total mass was 80 kg. In physiological trials [McLellan 1991], subjects wore impermeable gloves, masks and boots that covered an estimated 15% of the body surface area. For simplicity, it was assumed that this 15% of the body surface area did not participate in the transfer of heat or moisture from the body. While this is valid for moisture transport, it is only an approximation for heat transfer. Since ambient temperatures were close to body temperatures, the dry heat transfer would be a small component of the total heat transfer and so the error incurred with this approximation should not be important.

Respiration rates and the accompanying energy loss were calculated from empirical results [Cain 1989], the data being fitted to the following linear relationship between ventilation rate and metabolic rate:

$$\frac{V-V_o}{V_o} = 0.66 * \frac{Q_{met}-Q_{met_o}}{Q_{met_o}} \qquad (1)$$

where V is the ventilation rate in litres per minute and the reference conditions used are V_o = 10.7 l/min and Q_{meto} = 97 W. This relationship was derived from a small sample population of subjects working from approximately 100 W to 500 W and was found to have a very good correlation over this range. It is doubtful that this equation would be valid at higher work rates (say greater than about 1000 W) as the respiration rate is known to approach a maximum and the metabolic rate becomes increasingly anaerobic with increasing metabolic rate.

Sweat rates were estimated from a relationship involving skin and core temperatures [Fortney 1985]. Sweat rates were found to vary approximately bi-linearly both with oesophageal temperature and skin temperature. For this study, it was assumed that core and oesophageal temperatures were equivalent. The numerical relationship between these parameters was estimated to be:

$$m_s = 0.0625 * (T_c - 37.2) + 0.03 * (T_s - 34) \qquad (2)$$

where m_s is the sweat rate (g/s), T_c is the core temperature (°C) and T_s is the skin temperature (°C). If the core temperature was below 37.2°C or the skin temperature was below 34°C, it was assumed that no sweating occurred.

Evaporation from the skin depends upon the vapour pressure difference across the clothing and the clothing's resistance to water vapour transport. Maximum evaporation occurs when the skin is saturated, however, the sweat rate may be greater or less than the maximum evaporation rate. In this study, evaporation rate was limited to the maximum noted here and any excess water from sweating was assumed to collect within the clothing but not to have any effect on the heat and water vapour transport. If sweating occurred at a rate less than the maximum evaporation rate, all of the sweat was assumed to evaporate and this quantity was used to calculate the evaporative heat transfer. The saturation vapour pressure at the skin and in the environment were calculated from empirical relationships which depend only upon temperature [Weast 1987].

The efficiency of the human body in converting chemical energy into useful, external work varies depending upon the activity. For this study, it was assumed that only 10% of the total metabolic rate was expended as external work and this energy was deducted from that which must be dissipated as heat.

2.2 Numerical Approach

The two equations used to describe the temperature and heat flow from the body are simple, linear but simultaneous as the conductive core heat loss term will depend on the skin temperature. The heat and water vapour capacities of the garments are small compared with that of the body and have been ignored. Thus, the only temporal derivative terms are the core and skin temperatures, or equivalently the body heat storage terms.

The rate of heat storage of the core is equal to the metabolic rate, Q_{met}, minus the respiratory heat loss, Q_{resp}, the external work, W_{ext}, and the heat loss from the core to the skin, Q_c:

$$m_c c_p \frac{dT_c}{dt} = Q_{met} - Q_{resp} - W_{ext} - Q_c \qquad (3)$$

Here, m_c is the body mass contained in the core, c_p is the body heat capacity (estimated to be 3.486 J/gK), T_c is the core temperature and t is time.

The rate of heat storage in the skin region is equal to the rate of heat transfer to the skin from the core region minus the dry (conductive and radiative) heat loss from the skin to the environment, Q_{dry}, and the evaporative heat loss from the skin, Q_{evap}:

$$m_s c_p \frac{dT_s}{dt} = Q_c - Q_{dry} - Q_{evap} \tag{4}$$

In this equation, m_s is the mass of the skin layer and T_s is the skin temperature.

These equations were solved numerically using a two step, predictor-corrector method similar to that used in finite difference methods. In the predictor step, the temporal derivatives were evaluated using a backwards differencing scheme to obtain the core and skin temperatures at the current timestep, j. Other terms in the equations were evaluated at the previous timestep, j-1. This yielded the following form for equations 3 and 4 for the predictor step:

$$m_c c_p \frac{T_c^j - T_c^{j-1}}{\Delta t} = Q_{met}^{j-1} - Q_{resp}^{j-1} - W_{ext}^{j-1} - Q_c^{j-1} \tag{5}$$

$$m_s c_p \frac{T_s^j - T_s^{j-1}}{\Delta t} = Q_c^{j-1} - Q_{dry}^{j-1} - Q_{evap}^{j-1} \tag{6}$$

The core and skin temperatures obtained from these equations were used as an initial guess for the corrector step as well as the first time step in the integration. For the third and subsequent timesteps, these estimates were improved using the corrector equations. In the corrector step, temporal derivatives were evaluated using a central differencing scheme to obtain the desired temperatures at the next timestep, j+1. Other terms in the equations were evaluated at the current timestep, j. This resulted in the following equations:

$$m_c c_p \frac{T_c^{j+1} - T_c^{j-1}}{2\Delta t} = Q_{met}^j - Q_{resp}^j - W_{ext}^j - Q_c^j \tag{7}$$

$$m_s c_p \frac{T_s^{j+1} - T_s^{j-1}}{2\Delta t} = Q_c^j - Q_{dry}^j - Q_{evap}^j \tag{8}$$

The difference between the "predicted" temperatures and the "corrected" temperatures at each timestep were compared to a tolerance value. If either of the differences was greater than this tolerance, the corrected values were substituted for the predicted temperatures and the corrector equations were evaluated again. This procedure was repeated until the tolerance criteria were satisfied. A tolerance of 0.001°C was used for both core and skin temperature calculations.

Two different conditions were examined which are similar to the conditions studied in a physiological experiment [McLellan 1991]. First, a light work-rest cycle was studied. The metabolic rate alternated between a working rate of 350 W and a resting rate of 110 W (experimental values were 364 W and 106 W respectively). Each work or rest cycle lasted 15 minutes and the metabolic rate was assumed to change instantly at the beginning of each cycle. The second condition studied was a moderate, continuous work rate of 490 W (the experimental value was 504 W). In both cases, the ambient temperature selected was 40°C and the relative humidity selected was 27.5% to match experimental conditions.

The timestep size used in the analysis was 1 second for all tests. Results were recorded every 60 timesteps and the tests went on for 3 hours. The analysis actually took only several minutes of execution time on a 12 Mhz 80286 computer for each three-hour experiment. A listing of the program used is presented in Appendix A.

The data required for each ensemble were as follows: the ensemble name; the number of fabric layers in the ensemble; the thermal resistance and water vapour diffusion length of each fabric layer and air layer. The units of thermal resistance are m^2K/W and the water vapour diffusion length is in the equivalent thickness in millimetres of still air. A sample of the input data is given in Appendix B.

2.3 Clothing Description

Four different versions of two protective clothing ensembles were studied. These ensembles are the current Canadian Forces (CF) Nuclear, Biological, Chemical (NBC) Protective Suit; the NBC suit over CF combat fatigues; an experimental vapour protective garment developed at Defence Research Establishment Ottawa (DREO) referred to as the Interim suit; the Interim suit worn under CF combat fatigues. In all of the ensembles, the CF respirator was worn over the face, the CF NBC gloves where worn over the hands and the CF NBC overboots were worn over the CF combat boots.

The current CF NBC suit is a one-piece, loose fitting, hooded coverall. It is made of a charcoal-impregnated, open-cell foam with a liquid repellent, cotton-nylon shell fabric. The garment thickness is approximately 3 mm with a thermal resistance of 0.07 m^2K/W and a water vapour permeability equivalent to 8.2 mm of still air.

The DREO Interim suit is a two-layer, two-piece garment. The inner layer is a tight fitting, stretchable, polyester long-underwear. These garments cover the legs, arms and torso and are worn to provide a barrier between the skin and the charcoal in the outer layer. The outer layer is a charcoal-impregnated, lycra trousers and hooded top, intended to provide chemical vapour protection. Due to the technique used to impregnate the lycra with charcoal, much of the fabric's original stretch was lost. The garment was tailored to be relatively close fitting and the remaining stretch was adequate for comfort and movement. The thickness of the fabrics in these garments is approximately 0.5 mm.

The combat fatigues are the current CF issue; a cotton-nylon blend approximately 0.5 mm thick. The numerous pockets and reinforcing patches were ignored in this study.

The clothing ensembles were modeled as an assembly of still air and fabric layers. The thermal resistance of each layer had been determined in another study [Cain 1991] and the values of thermal resistance and water vapour diffustion length of each layer are simply presented in Appendix B. Water vapour resistances were measured or estimated based on layer thicknesses.

3.0 Results and Discussion

Figure 1 shows the predicted core and skin temperature responses for the case of a work/rest cycle. The skin temperature rises quickly over the first few minutes until sweating occurs and evaporative heat loss begins to dominate the heat loss. The temperatures cycle as the metabolic rate changes during the work and rest cycles.

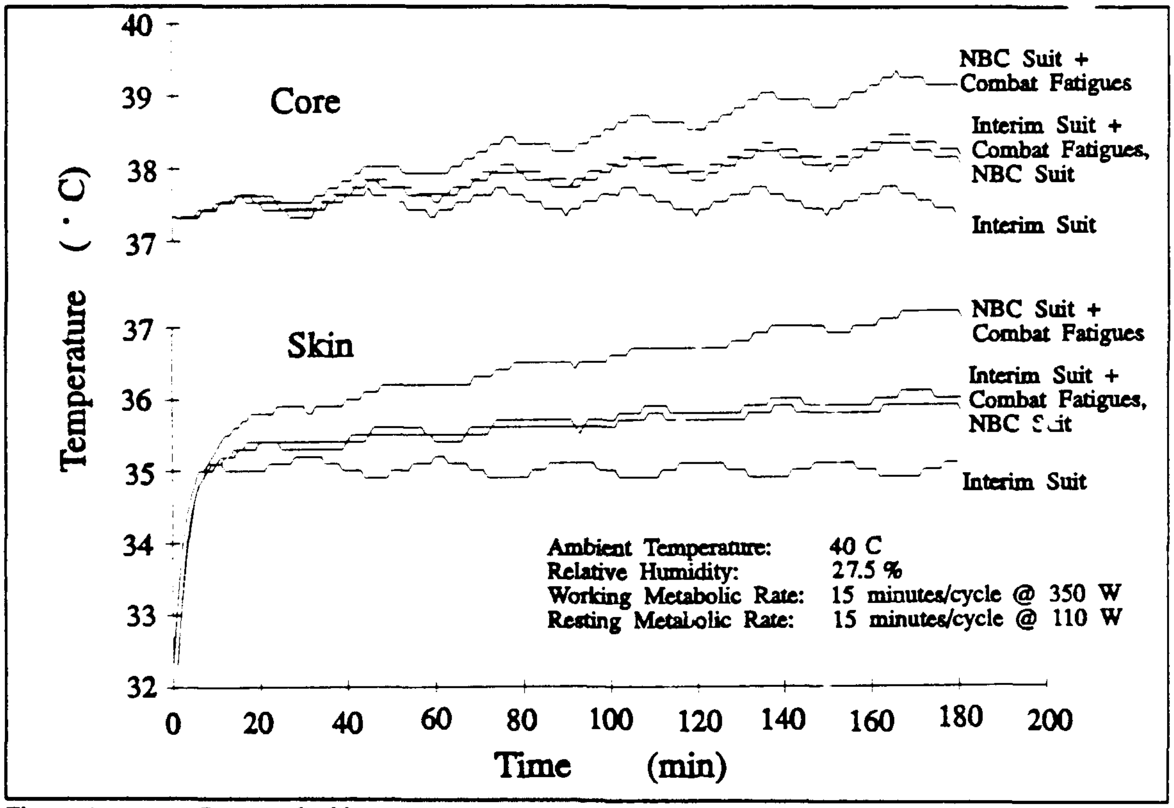

Figure 1. Core and skin temperature responses during a work/rest test in several different ensembles.

The results indicate that the core and skin temperatures for the interim garment reach an equilibrium state but the temperatures for the other ensembles continue to slowly increase. The Interim suit worn beneath the combat fatigues has virtually the same effect on the body temperatures as the NBC garment alone. The NBC garment worn over the combat fatigues is seen to cause the greatest heat stress of the garments studied.

The results for the physiological work/rest experiments were reported up to 100 mir. ites. Qualitatively, the model and the experimental results are quite similar, although the rate of increase of the skin temperature predicted by the model is somewhat greater than that observed in the experiments. The skin temperatures predicted by the model tended to be about 1°C lower than that observed in the experiments. Part of the difference is due to the difference in the average initial temperatures for each garment in the experiments which appeared to be as great as 1°C. A more representative comparison would be to compare average change in temperature from the initial temperature as a function of time.

There are other factors, both numerical and experimental, which probably lead to discrepancies between the results of the two techniques. The mathematical model has limits on its accuracy as it dramatically simplifies a number of physical and physiological variables. In the experimental analysis, the mean skin temperature is calculated based on measurements at discrete locations. If the temperature sensors at these locations happen to be positioned under uncharacteristically close fitting areas of the clothing, then the mean temperature would be greater than expected. Also, the sensors may be exposed to frictional heating as the clothing slides over the body, a factor not considered at all in the numerical analysis and only indirectly in the physiological experiment. These concerns demonstrate the limitations or advantages of the two differing techniques and emphasise the fact that each technique compliments rather than competes with the other.

The model's core temperature predictions did not rise as quickly as the experimental values and the oscillations accompanying the work/rest cycles were more pronounced in the model. The model predictions tended to be about 0.5°C lower than the experimental values at 100 minutes.

In the physiological study, several failure criteria were used to terminate the experiment: a core temperature of 39.3°C; a heart rate greater than 95% of maximum for three continuous minutes; dizziness or nausea. Since no attempt was made to model the body's heart rate, and the computer rarely gets dizzy, only the core temperature criterion predicted by the model can be compared to the experimental data. The model is thus less stringent and longer tolerance times are likely to be predicted. Unfortunately, no differentiation between failure causes was made in the physiological report so comparison of work tolerance times based on core temperature alone is not possible.

Model predictions for the failure time for the NBC Suit over combat fatigues was 165 minutes compared to 115 minutes found experimentally. The model predicted that the Interim Suit worn under combat fatigues and the NBC Suit worn alone would not fail until after the 180 minute limit of the experiment while it was found experimentally that the NBC Suit worn alone failed after 140 minutes. The Interim suit worn alone gave no indication of approaching the failure criterion in both the model prediction and the experimental measurements.

Figure 2 shows the predicted core and skin temperature responses for the case of continuous, moderate word and the trends are somewhat different. In this case, all temperatures increase with time for all ensembles and give no indication of leveling off as predicted in the previous case. The skin temperatures increase rapidly until sweating and evaporative heat loss becomes dominant as in the case with work/rest cycles. After the initial, rapid increase, the skin temperatures continue to rise but at a slower rate. The results from the physiological experiments for the continuous work case were reported up to approximately 30 minutes. Again the model predicts a greater rate of increase of the skin temperature than was observed. The values attained at the end of the experiments were slightly greater than that of the model for the NBC suit both with and without combat

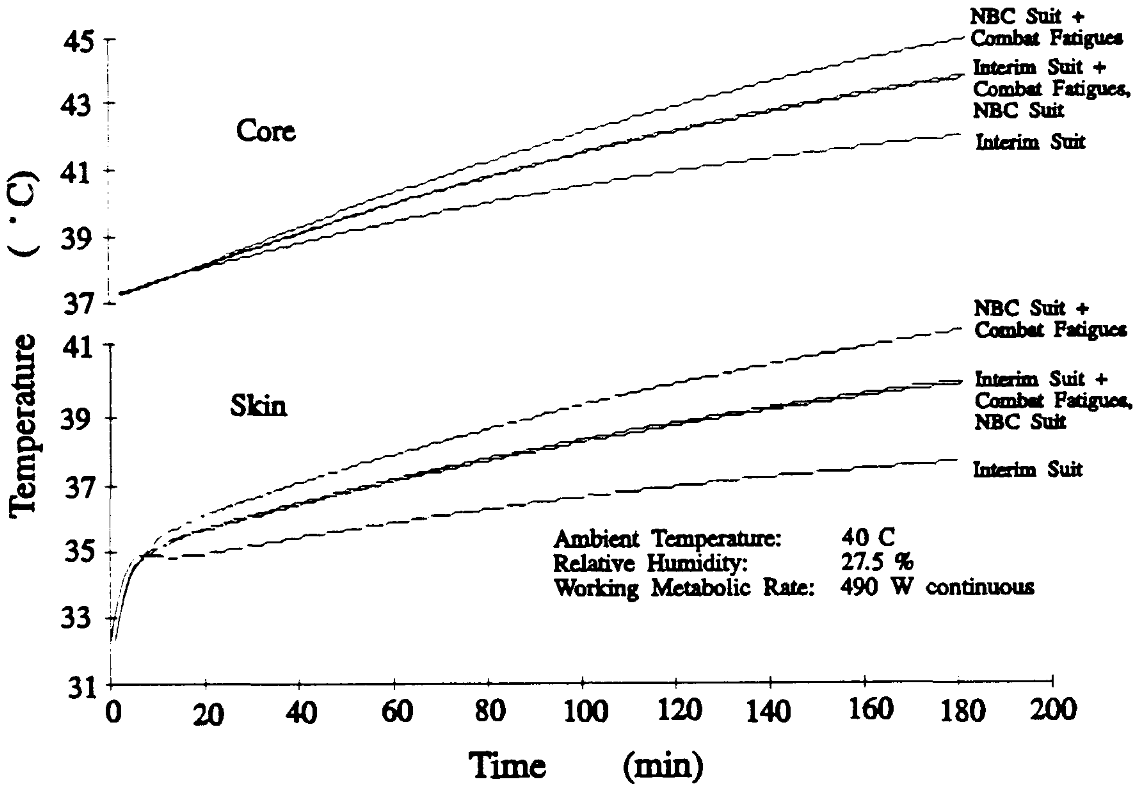

Figure 2. Core and skin temperature responses during a continuous, moderate work test in several different ensembles.

fatigues. The skin temperature under the Interim suit was noticeably greater (~1°C) in the experiments compared to the predicted temperature. Core temperatures seemed to be quite comparable between the model and experimental results.

Using the failure criterion of 39.3°C for the continuous work case, all ensembles were predicted to fail but they maintained their relative ranking for causing heat stress. The NBC suit over combat fatigues was predicted to fail at approximately 40 minutes which compares well with the 46 minutes found experimentally. The NBC suit alone and the Interim suit with combat fatigues were predicted to fail at approximately 47 minutes into the test while the subjects actually lasted for approximately 60 minutes. The Interim suit was predicted to fail at approximately 60 minutes while the subjects continued for 85 minutes in the experiments.

The Interim suit causes less heat stress in a hot environment because of its lower resistance to water vapour diffusion which allows greater evaporative heat loss. In Figure 3, the relative importance of the different avenues of heat loss for the body are shown for the work/rest test. Similar results are found for the continuous work test.

Since the ambient temperature is greater than the skin temperature, dry heat loss is negative; that is, the body is gaining heat by conduction and radiation. This gain is fortunately small due to the small temperature difference and the thermal resistance offered by the garments. In this respect, the garments with higher thermal

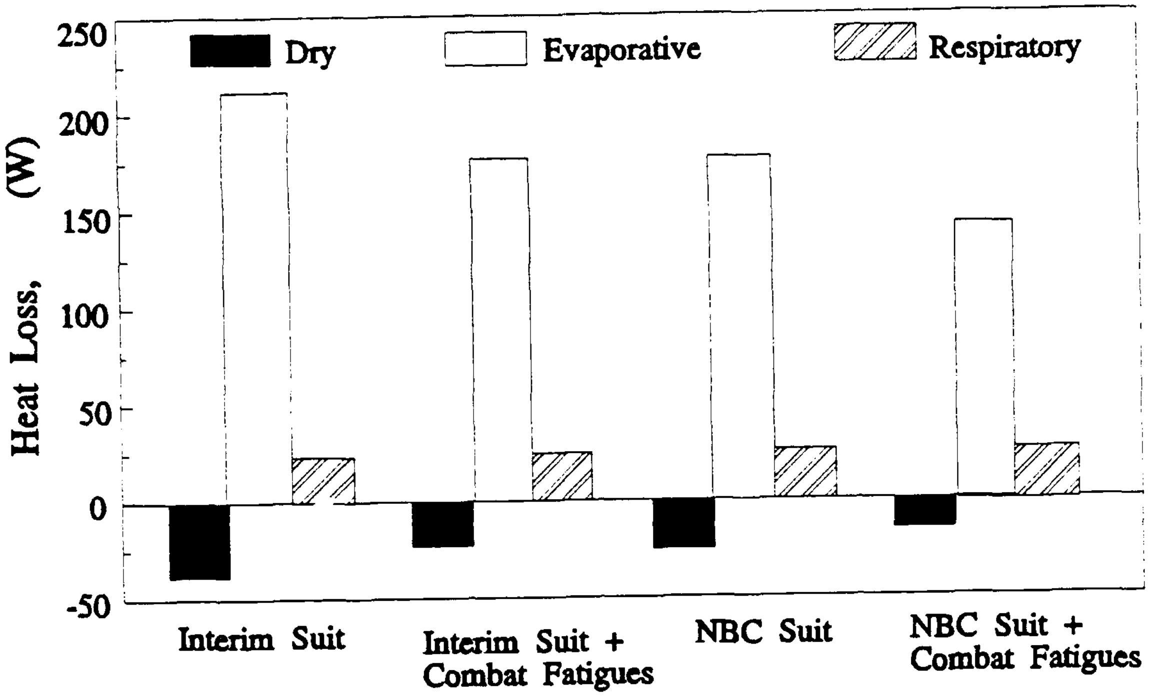

Figure 3. Typical contributions by the different heat loss mechanisms to the total heat loss from the body during a work/rest test.

resistance, such as the NBC garment worn over the combat fatigues, have an advantage over the other ensembles but the advantage is negated by the accompanying high resistance to water vapour diffusion.

Evaporation from the skin can be seen to be the dominant heat loss mechanism in all cases. The thinner garments with the high water vapour permeability have a substantially greater heat loss because of this. Evaporative heat loss has long been recognised as an important means for the body to regulate its temperatures. Respiratory heat loss, which is in large measure due to evaporation as well, was estimated to represent between 10 and 15% of the total heat loss.

Except for the Interim garment, the rate of sweat production predicted and measured showed reasonable agreement in the work/rest tests. For the Interim garment, the predicted sweat rate was 0.08 g/s compared to approximately 0.14 g/s of the experiments. The NBC suit had a predicted sweat rate of 0.17 g/s compared to a measured 0.19 g/s and the NBC suit over combat fatigues had a predicted sweat rate of 0.26 g/s compared to a measured 0.21 g/s. Given the simple empirical relationship used in the model and the numerous sources of error possible in the experimental measurements, these values are in good agreement. Such was not the case, however, for the predicted sweat production rate in the continuous work tests. In these cases, the predicted sweat rates were about twice that measured. This may be due to the simplicity of the empirical model used, as

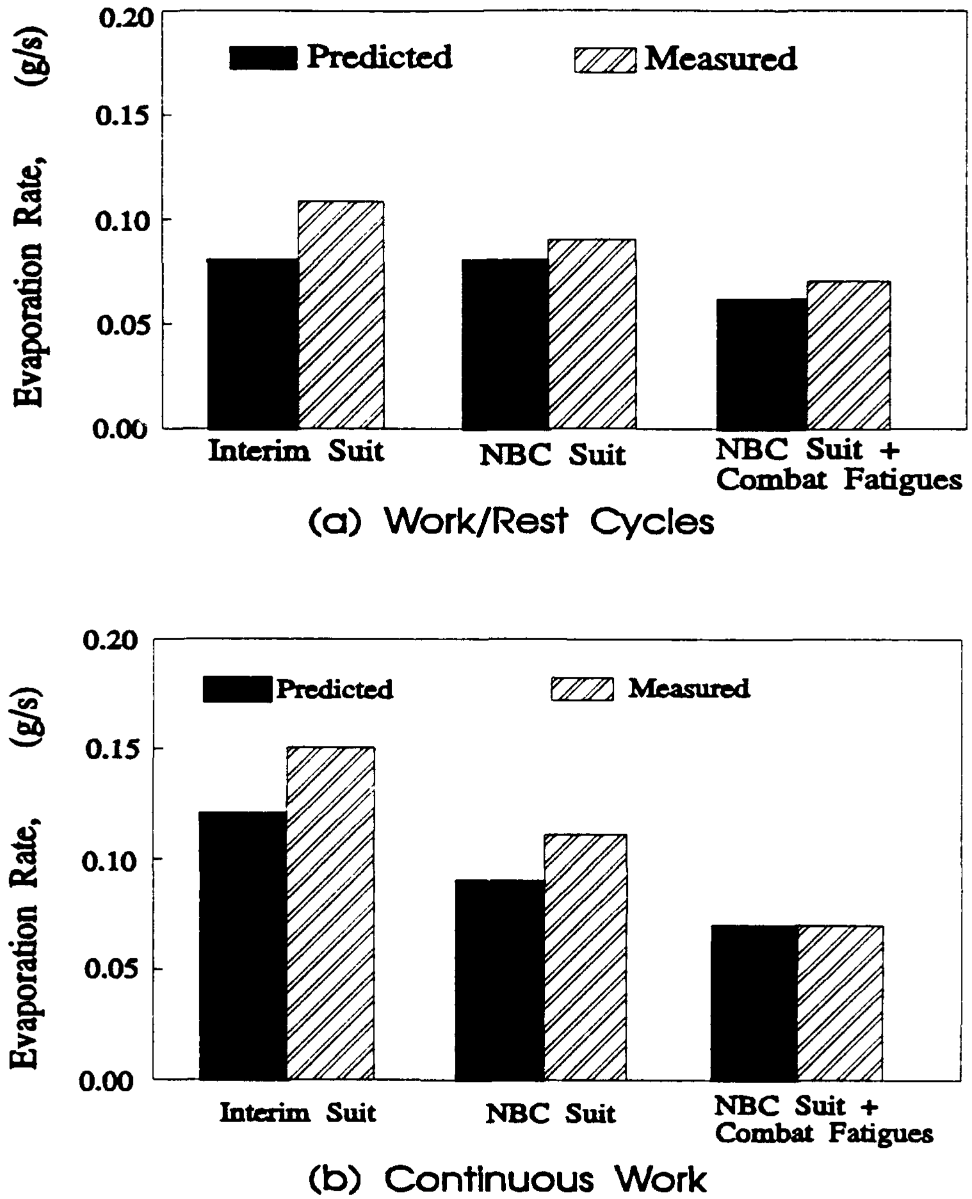

Figure 4. Comparison of mean evaporation rates through NBC clothing ensembles.

no maximum limit was placed on the sweat rate which is not physically realistic. There may also be factors other than skin and core temperature which govern the rate of sweat production or the onset of sweating that were not included in the model.

The rate of evaporation rather than the rate of sweating is perhaps of more relevance to the thermal regulation. The evaporation rate was calculated for the experimental tests from the quoted sweat production rates and evaporative efficiency values. Figure 4 shows both the predicted and measured evaporation rates for the various garments with good agreement in all cases. The two NBC suit ensembles have lower evaporation rates, although the difference is more pronounced in the experimental results than in the model results.

Studies of solar radiation and forced ventilation by the wind on the heat transfer across these garments were not done, so a quantitative analysis of the performance of each ensemble to these variables was not possible. Other than the rather simple observation that solar radiation will decrease and the wind will increase the net heat loss from the body, little can even be qualitatively predicted with any degree of confidence.

4.0 Conclusions

Of the four ensembles studied, the Interim suit worn alone was found to cause the least amount of heat stress. This was primarily due to its greater evaporative heat loss resulting from its lower water vapour diffusion resistance. Indeed, evaporative heat loss is the only mechanism which keeps the body temperatures within safe limits in an environment in which the dry bulb temperature and radiant temperature are both greater than the skin temperature. When the Interim suit was worn under combat fatigues, the incurred heat stress was predicted to be the same as that for the NBC suit worn alone. The NBC suit was found to be the most heat stressful due to its high resistance to water vapour diffusion.

The results indicate that, for a hot environment, an ensemble with a high thermal resistance but with a very low water vapour diffusion resistance would be ideal. This may be increasingly true when solar radiation enters into the problem. Unfortunately, high thermal resistance often implies high water vapour diffusion resistance in passive clothing ensembles. In order to meet both objectives, an active or wind ventilated system is likely required in which the thermal resistance is by-passed by forced ventilation close to the body.

The differences between the model and experimental results were occasionally significant, however, in most cases the results were not vastly different. There was qualitative agreement in all cases. The differences reinforce the idea that the two evaluation techniques are complimentary, each with its own advantages and disadvantages.

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__Appendix A__ Program listing used to evaluate the governing equations.

The following is the program used to analyze the various ensembles. It is written in Microsoft QuickBasic 4.0. Software constraints dictate that the program must be compiled and run as an executable program rather than an interpreted program within the Microsoft QuickBasic environment. A sample input data file (called "htin.dat in the program) is given in Appendix B.

```
DECLARE FUNCTION sweat# (tcore#, tskin#)
DECLARE FUNCTION pwv# (t#)
DECLARE FUNCTION dwv# (t#)
DECLARE FUNCTION humid# (t#, rh#)
DECLARE FUNCTION dens# (t#)
DECLARE FUNCTION qresp# (tcore#, tamb#, hrair#, mr)
'
'Program:  Htstr6.bas
'
' This program is a simple model of a body's response to work in a hot environment wearing user defined
' clothing ensembles. Solar radiation is not accounted for nor is ventilation of the clothing.
'
DEFDBL A-H, O-Z
DEFSNG M
DIM name$(20), nlayers(20), rt(20, 20), lwv(20, 20), rttot(20), lwvtot(20)
'
CLS
'
OPEN "c:\htin.dat" FOR INPUT AS #1
OPEN "c:\htout.dat" FOR OUTPUT AS #2
'
'Program Constants
'
bmass = 80000          ' g  -  Body mass
fskin = .1             ' fraction of the body mass which is the skin layer
fcore = .9             ' fraction of the body mass which is the core
area = 1.8             ' m^2  -  Body surface area
tdur = 180 * 60        ' s  -  Test duration
tstep = 1              ' step size in seconds
nprint = 60 / tstep    ' save results every minute, ie every nprint steps
rgas = 8.314           ' N m/gmole K  -  Universal Gas Constant
mh20 = 18              ' g/gmole  -  Molecular weight of water
hfg = 2419             ' J/g  -  Enthalpy of evaporation
cp = 3.486             ' J/g K  -  Specific Heat the body
cpa = 1                ' J/g K  -  Specific Heat of air
cpv = 1.9              ' J/g K  -  Specific Heat of water vapour
```

```
rtcore = .025              ' m^2 K/w  - Thermal Resistance between the core and the skin
eff = .1                   ' working efficiency = fraction of metabolic rate expended
'                                 as usefull work
ccore = fcore * bmass * cp        ' a core constant
cskin = fskin * bmass * cp        ' a skin constant
accf = 1                   ' acceleration factor to limit step changes in temperature
'
PRINT #2, "Body Mass, kg:  "; bmass / 1000
PRINT #2, "Body Area, m^2:  "; area
PRINT #2,
'
'Enter the ambient conditions
'
INPUT ; "Ambient Temperature, C "; tamb
PRINT #2, "Ambient Temperature, C:  "; tamb
PRINT " "
INPUT ; "Ambient Relative Humidity, 0<RH<1 "; rh
PRINT #2, "Ambient Relative Humidity:  "; rh
PRINT " "
PRINT #2,
pambs = pwv(tamb)              ' Pa  -  Saturated ambient vapour pressure
pamb = pambs * rh              ' Pa  -  Ambient water vapour pressure
hrair = humid(tamb, rh)        ' kg-water/kg-air  -  ambient humidity ratio
'
'Enter the work rest cycles
'
PRINT " "
PRINT " "
INPUT ; "Working Metabolic Rate, [W]:  ", mrwork
PRINT " "
PRINT " "
INPUT ; "Work duration, [minutes]:  ", twork
PRINT #2, "Working Met Rate, W:  "; mrwork; "  Duration, min:  "; twork
PRINT " "
PRINT " "
INPUT ; "Resting Metabolic Rate, [W]:  ", mrrest
PRINT " "
PRINT " "
INPUT ; "Rest duration, [minutes]:   ", trest
PRINT #2, "Resting Met Rate, W:  "; mrrest; "  Duration, min:  "; trest
PRINT #2,
twork = twork * 60    ' convert times to seconds
trest = trest * 60
```

```
PRINT " "
PRINT " "
tcyc = twork + trest      ' duration of 1 work/rest cycle in seconds
'
'Enter the initial body conditions
'
INPUT ; "Initial Core Temperature, C: ", tcorei
PRINT
INPUT ; "Initial Skin Temperature, C: ", tskini
PRINT #2, "initial core temp"; tcorei
PRINT #2, "initial skin temp"; tskini
avgt = (tskini + tamb) / 2        ' C - estimate of typical clothing temperature
INPUT #1, nsuits
PRINT #2, "Number of Ensembles: "; nsuits
PRINT #2,
'
'Read in the data
'
FOR i = 1 TO nsuits
'
  INPUT #1, name$(i)        'Ensemble name
  INPUT #1, nlayers(i)      '# of fabric layers
'
  PRINT #2,
  PRINT #2, "Ensemble Name:  "; name$(i)
  PRINT #2, "Number of Layers:  "; nlayers(i)
  PRINT #2,
'
  jmax = 2 * nlayers(i) + 1          'total # of air + fabric + boundary layers
'
'Read in the individual fabric and air layer resistances
'
FOR j = 1 TO jmax
'
  INPUT #1, rt(i, j), lwv(i, j)          'thermal resist and wv diff. length of each layer
  rttot(i) = rttot(i) + rt(i, j)         'total ensemble thermal resistance in m^2 K/W
  lwvtot(i) = lwvtot(i) + lwv(i, j)      'ensemble wv resist  mm of SA
'
NEXT j
'
  rwvtot(i) = lwvtot(i) * rgas * (avgt + 273) / (1000 * mh20 * dwv(avgt))  ' Pa  m^2  s/g  -  water  vapour
'                                                                              resistance of the ensemble
```

```
  PRINT #2, "Total Thermal Resistance, m^2 K/W:  "; rttot(i)'
  PRINT #2, "Total Water Vapour Resistance, Pa m^2 s/g: "; rwvtot(i)
  PRINT #2, "Total Water Vapour Resistance, mm S.A.:  "; lwvtot(i)
  PRINT #2,
  PRINT #2,
'
'NEXT i
'
' Perform the analysis for each ensemble consecutively
'
'FOR i = 1 TO nsuits
'
  mext = 0                    ' g - mass of surplus sweat; stays in clothing
  j = 1
  thyme = 0
  tcorejm1 = tcorei
  tskinjm1 = tskini
'
  PRINT #2, USING "#####.#"; thyme; tcorejm1; tskinjm1
'
FOR thyme = tstep TO tdur STEP tstep
'
  j = j + 1
  CLS
  nmin = thyme \ 60
  PRINT "Analysing suit "; i; " of "; nsuits
  PRINT "Computation is at time "; nmin; " minutes of "; tdur / 60
'
' Determine which phase of the work/rest cycle you are in and select
' the appropriate work rate
'
  ft = ((thyme / tcyc) - (thyme \ tcyc)) * tcyc     ' time thru the cycle
'
  IF ft <= twork THEN
    mr = mrwork                                ' Metabolic Rate in Watts
  ELSEIF ft > twork AND ft <= tcyc THEN
    mr = mrrest                                ' Metabolic Rate in Watts
  ELSE
    PRINT ; 'Error in ft:  ';ft
  END IF
'
  qcore = (tcorejm1 - tskinjm1) * area / rtcore   ' W - Core heat loss
  qr = qresp(tcorejm1, tamb, hrair, mr)          ' W - Resp Heat Loss
```

```
'
' Calculate the new core temperature
'
  rhscjm1 = (1 - eff) * mr - qr - qcore
  dtcore = tstep * rhscjm1 / ccore
  tcorej = tcorejm1 + dtcore
'
' Calculate the dry heat loss from the skin
'
  qdry = (tskinjm1 - tamb) * area / rttot(i)        ' Watts
'
' Calculate the rate of sweating
'
  msweat = sweat(tcorejm1, tskinjm1) * area      ' g/s
'
'Calculate the maximum evaporative rate assuming saturated skin conditions
'
  mevap = (pwv(tskinjm1) - pamb) * area / rwvtot(i)      ' g/s
'
' If the sweat rate is greater than the evaporative rate, then only allow
' the maximum evaporative rate to occur. Collect extra sweat.
'
  IF msweat > mevap THEN
    mext = mext + (msweat - mevap) * tstep    ' g - mass of unevap sweat
    qevap = hfg * mevap                       ' W - evaporative heat loss
  ELSE
    qevap = hfg * msweat                      ' W - evaporative heat loss
  END IF
'
' Calculate the new skin temperature
'
  rhssjm1 = qcore - qdry - qevap
  dtskin = tstep * rhssjm1 / cskin
  tskinj = tskinjm1 + dtskin
'
' Reinitialize values for the next timestep
'
  tcorejm1 = tcorej
  tskinjm1 = tskinj
'
    IF j / nprint = j \ nprint THEN
      PRINT #2, USING "#####.#"; thyme / 60; tcorej; tskinj
    END IF
```

```
'
NEXT thyme
NEXT i
'
END
STOP

FUNCTION dens# (t#)
DEFSNG A-H, O-Z
DEFDBL A-H, O-Z
'
' This function calculates the density of dry air
'
' Input is the air temperature in degrees Celsius
' Output is density in kilograms per cubic metre
'
dens = 353 / (t + 273)  ' kg/m^3
'
END FUNCTION

FUNCTION dwv# (t#)
DEFSNG A-H, O-Z
DEFDBL A-Z
'
'This program calculates the water vapour diffusivity in air.  Pressure dependence has been ignored.
'
'Input is the air temperature in degrees Celsius
'Output is the water vapour diffusivity in m^2/s
'
d0 = .0000226            'm^2/s,  reference diffusivity at 0C
t0 = 273.16             'C,  reference temperature
n = 1.81                'temperature ratio dependence exponent
'
dwv = d0 * ((273.16 + t) / t0) ^ n   'm^2/s
'
END FUNCTION

FUNCTION humid# (t#, rh#)
DEFSNG A-Z
DEFDBL A-H, O-Z
'
' This funciton calculates the Humidity Ratio at the specified temperature
' and RH.
```

```
'
' Inputs are the air temperature in degrees Celsius and the Relative Humidity
' Output is the mass of water vapour per unit mass of dry air.
'
rair = 278                          ' N m /kg K, gas constant for air
'
pw = rh * pwv(t)                    ' Water Vapour Pressure, Pa
pa = dens(t) * rair * (t + 273)     ' Air Pressure, Pa
'
humid = .62198 * pw / pa            ' Humidity Ratio, kg-water/kg-air
'
END FUNCTION

FUNCTION pwv# (t#)
DEFSNG A-H, O-Z
DEFDBL A-H, O-Z
'
'    This program calculates the saturation water vapour pressure
'
'    Input is the air temperature in degrees Celsius
'    Output is the saturation water vapour pressure in Pascals
'
DIM f(8)
'
IF t >= 0 THEN
'
'        Vapour Pressure over liquid water: 0C <= t <= 374C
'
'Constants from the Goff Formulas, ASHREA Fundamentals Handbook
f(1) = -741.9242
f(2) = -29.721
f(3) = -11.55286
f(4) = -.868564
f(5) = .1094098
f(6) = .439993
f(7) = .2520658
f(8) = .0521868
'
sum = 0
'
FOR i = 1 TO 8
  sum = sum + f(i) * (.65 - .01 * t) ^ (i - 1)
NEXT i
```

```
  temp = .01 * (374.136 - t) * sum / (t + 273.16)
  pwvl = 217.99 * EXP(temp)                    ' Pressure in atmospheres
'
ELSE  ' t < 0
'
'       Vapour Pressure over ice:  -100C < = t < = 0C
'
  theta = 273.16 / (t + 273.16)
  temp = -9.096936 * (1 - theta) - 1.5489 * LOG(theta)
  temp = temp + (1.50474 * 10 ^ -4) * (1 - 10 ^ -8.29692 * (1 / theta - 1))
  temp = temp + (.42873 * 10 ^ -3) * (10 ^ 4.76955 * (1 - theta) - 1) - 2.2195983#
'
  pwvl = EXP(temp / .43429)                    ' Pressure in atmospheres
END IF
'
pwv = pwvl * 101200                            ' Pressure in Pascals
'
END FUNCTION

FUNCTION qresp# (tcore#, tamb#, hrair#, mr)
DEFSNG A-H, O-Z
DEFDBL A-H, O-Z
DEFSNG M
'
' This function makes an estimate of the heat lost due to respiration.
' It is highly empirical and probably isnt valid for work rates much in
' excess of 500 W.  The respiration rate is based on experimental observations
' of several test subjects at DREO.
'
'  The required inputs are:
'    tcore  -  core temperature in C
'    tamb   -  ambient temperature in C
'    hrair  -  ambient humidity ratio in mass H2O/mass dry air
'    mr     -  metabolic rate in Watts
'
'  The output is the respiratory heat loss in Watts
'
   cpa = 1                  ' J/g K  -  Specific Heat of Dry Air
   cpv = 1.9                ' J/g K  -  Specific Heat of water vapour
   hfg = 2419               ' J/g    -  Enthalpy of Evaporation for water
   v0 = 8.7                 ' l/min  -  Reference Respiration Rate
   m0 = 76                  ' W      -  Reference Metabolic Rate
'
```

```
  a1 = cpa * (tcore - tamb)
  a2 = hfg * (humid(tcore, 1) - hrair)
  a3 = hrair * cpv * (tcore - tamb)
'
  vresp = v0 * (1.05 + .644 * (mr - m0) / m0)          ' l/m - resp rate
  qresp = dens(tcore) * vresp * (a1 + a2 + a3) / 60   ' W - resp heat loss
'
END FUNCTION

FUNCTION sweat# (tcore#, tskin#)
DEFSNG A-H, O-Z
DEFDBL A-H, O-Z
'
' This function estimates the sweat rate based on core temperature and skin temperature. This scheme is based
' on information found in an artical by Fourtney in the Journal of Sports Med (2) 1985. This is a pretty crude
' model and probably isn't valid below core temperatures of 37 or skin temperatures above 36.
'
' Inputs are the core temperature and the skin temperture in degrees Celsius
' Output is the sweat rate in g/s/m^2
'
IF tcore < 37 THEN
  sweat = 0                    ' no sweating occurs
ELSE
  temp = .0625 * (tcore - 37.2) + .03 * (tskin - 34)  '  g/s/m^2
  IF temp < 0 THEN
    sweat = 0
  ELSE
    sweat = temp
  END IF
END IF
'
END FUNCTION
```

Appendix B Input data for the program.

The following is a sample listing of the data from a file "htin.dat" read by the model program. The first datum is the number of ensembles to be tested. This is followed by the data for each ensemble which are: the ensemble name; the number of clothing layers; the thermal resistance (m^2K/W) and water vapour diffusion resistance (mm of equivalent still air).

```
4
interim
2
0.   0.
0.01  1.
0.1   5.
0.01  1.
0.12  5.
interim & combat fatigues
3
0  0
.01   1.
.1    5.
.01   1.
.1    5.
.01   1.
.12   5.
NBC Suit
1
.1  5.
.09  8.2
.12  5.
nbc & combat fatigues
2
0.1   5.
0.01  1.
0.1   5.
0.09  8.2
0.12  5.
```

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This report summarizes work done to model the heat and moisture transport through various NBC clothing ensembles. The analysis involves simplifying the three dimensional physical problem of clothing on a person to that of a one dimensional problem of flow through parallel layers of clothing and air. Body temperatures are calculated based on prescribed work rates, ambient conditions and clothing properties. Sweat response and respiration rates are estimated based on empirical data to provide appropriate boundary conditions at the skin. Core and skin temperatures are calculated during the analysis and reported as functions of time for four different clothing ensembles. Evaporative heat loss was found to be the dominant heat loss mechanism. Estimates of the rate of sweat evaporation through the clothing ensembles is made. The predicted temperature responses, although not exact, are comparable to results from physiological experiments but somewhat lower. Work tolerance times were predicted to be longer than that found experimentally.

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Moisture Transport
Heat Stress
Tolerance Time
Nuclear
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Chemical
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